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## Scalar and pseudoscalar Higgs production in association with a top-antitop pair

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### Abstract

We present the calculation of scalar and pseudoscalar Higgs production in association with a top-antitop pair to the next-to-leading order (NLO) accuracy in QCD, interfaced with parton showers according to the MC@NLO formalism. We apply our results to the cases of light and very light Higgs boson production at the LHC, giving results for total rates as well as for sample differential distributions, relevant to the Higgs, to the top quarks, and to their decay products. This work constitutes the first phenomenological application of aMC@NLO, a fully automated approach to complete event generation at NLO in QCD.

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## 1. Introduction

Establishing evidence for the Higgs boson(s), *i.e.*, the scalar remnant(s) of the Englert-Brout-Higgs mechanism [1, 2, 3] in the standard model and in extensions thereof, is among the most challenging goals of the LHC experiments. A coordinated theoretical/experimental effort in the last years has led to a number of remarkable achievements in the accuracy and usefulness of the available theoretical predictions, and in the role these play in current analysis techniques [4].

Depending on mass and couplings, Higgs bosons are produced and eventually decay in a plethora of different ways, leading to a wide range of signatures. In most cases, signals are difficult to identify because of the presence of large backgrounds, and reliable predictions are necessary firstly to design efficient search strategies, and secondly to perform the corresponding analyses. A particularly challenging scenario at the LHC is that of a standard-model light Higgs,  $m_H \lesssim 130$  GeV. In this case, the dominant decay mode is into a  $b\bar{b}$  pair, which is however completely overwhelmed by the irreducible QCD background. A possible solution is that of considering the Higgs in association with other easier-to-tag particles. An interesting case is that of a top-antitop pair, since the large Yukawa coupling  $t\bar{t}H$ , and the presence of top quarks, can be exploited to extract the signal from its QCD multi-jet backgrounds. Unfortunately, this production mechanism is also plagued by large backgrounds that involve a  $t\bar{t}$  pair, and hampered by its rather small rates, and thus turns out to be difficult to single out. Several search strategies have been proposed, based on different decay modes: from  $b\bar{b}$  which leads to largest number of expected events, to the more rare but potentially cleaner  $\tau\tau$  [5],  $WW^{(*)}$  [6] and  $\gamma\gamma$  [7] final states. All of them are in fact very challenging, and dedicated efforts need be made. For example, recently it has been argued that in the kinematical regions where the Higgs is at quite high transverse momentum the  $b\bar{b}$  pair would be merged into one “fat” jet, whose typical structure could help in discriminating it from QCD backgrounds [8, 9] (boosted Higgs scenario).

It is then clear that accurate and flexible simulations, for both signals and backgrounds, can give a significant contribution to the success of any given analysis. Predictions accurate to NLO in QCD and at the parton level for  $t\bar{t}H$  hadroproduction have been known for some time [10, 11, 12, 13, 14, 15], and recently confirmed by other groups [16, 17]. As for the most relevant background processes to the Higgs decay mode into  $b\bar{b}$ , NLO calculations for  $t\bar{t}b\bar{b}$  [18, 19, 20] and  $t\bar{t}jj$  [21] are available in the literature. In

this work, we extend the results for the signal to computing the associated production  $t\bar{t}A$  of a pseudo-scalar Higgs boson. All aspects of the calculations we present here are fully automated. One-loop contributions have been evaluated with MADLOOP [17], that uses the OPP integrand reduction method [22] as implemented in CUTTOOLS [23]. The other matrix-element contributions to the cross sections, their phase-space subtractions according to the FKS formalism [24], their combinations with the one-loop results, and their integration are performed by MADFKS [25]. The validation of MADLOOP and MADFKS in the context of hadronic collisions has been presented in Ref. [17]. For the sake of the present work, we have also performed a dedicated comparison with the results of Ref. [4] for the total  $t\bar{t}H$  cross section, and found agreement at the permille level for several Higgs masses.

We have also matched our NLO results with parton showers using the MC@NLO method [26]. This matching procedure has also been completely automated, and this work represents the first application of the MC@NLO technique to non-trivial processes which were previously available only at fixed order and at the parton level – in other words, to processes not already matched to showers by means of a dedicated, final-state-specific, software. What said above also implies that our results are the first example of NLO computations matched to showers in which *all* ingredients of the calculation are automated, and integrated in a unique software framework.

We remind the reader that the structure of the MC@NLO short-distance cross sections is the same as that of the underlying NLO computation, except for a pair of extra contributions, called MC subtraction terms. These terms have a factorised form, namely, they are essentially equal to the Born matrix elements, times a kernel whose main property is that of being process-independent. This is what renders it possible the automation of the construction of the MC subtraction terms, and ultimately the implementation of the MC@NLO prescription. We call aMC@NLO the code that automates the MC@NLO matching, and we defer its detailed presentation to a forthcoming paper [27]. aMC@NLO uses MADFKS for phase-space generation and for the computation of the pure-NLO short distance cross section of non-virtual origin, and on top of that it computes the MC subtraction terms. One-loop contributions may be taken from any program which evaluates virtual corrections and is compatible with the Binoth-Les Houches format [28]; as was said before, we use MADLOOP for the predictions given in this work. The resulting MC@NLO partonic cross sections

are integrated and unweighted by MINT [29], or by BASES/SPRING [30]<sup>1</sup>. aMC@NLO finally writes a Les Houches file with MC-readable hard events (which thus includes information on particles identities and their colour connections).

## 2. Results at the LHC

We present selected results for total cross sections and distributions relevant to  $t\bar{t}H/t\bar{t}A$  production at the LHC in three scenarios:

- I. Scalar  $H$ , with  $m_H = 120$  GeV;
- II. Pseudoscalar  $A$ , with  $m_A = 120$  GeV;
- III. Pseudoscalar  $A$ , with  $m_A = 40$  GeV;

where the Yukawa coupling to the top is always assumed SM-like,  $y_t/\sqrt{2} = m_t/v$ .

The three scenarios above allow one to compare the effects due the different parity of the Higgs couplings on total rates as well as on differential distributions. In this respect, it is particularly interesting to consider the situation in which the Higgs boson is light and pseudoscalar, as is predicted in several beyond-the-standard-model theories (see *e.g.* Refs. [31, 32, 33]). The main purpose of this section is that of studying the impact of QCD NLO corrections at both the parton level and after shower and hadronisation. For the numerical analysis we choose  $\mu_F = \mu_R = \left(m_T^t m_T^{\bar{t}} m_T^{H/A}\right)^{\frac{1}{3}}$ , where  $m_T = \sqrt{m^2 + p_T^2}$  and  $m_t^{pole} = m_t^{\overline{MS}} = 172.5$  GeV. We have used LO and NLO MSTW2008 parton distribution functions for the corresponding cross sections. The parton shower in aMC@NLO has been performed with Fortran HERWIG [34, 35, 36], version 6.520<sup>2</sup>.

The predicted production rates at the LHC running at  $\sqrt{s} = 7$  and 14 TeV are given in Table 1 where, for ease of reading, we also show the fully inclusive  $K$ -factor. As far as differential distributions are concerned, we

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<sup>1</sup>These integrators have been modified by us, in order to give them the possibility of dealing with both positive- and negative-weighted events.

<sup>2</sup>We remind the reader that the MC@NLO formalism has been employed to match NLO results with HERWIG++ [37] and, to a lesser extent, with PYTHIA [38] (see Ref. [39] and Ref. [40] respectively). The automation of the matching to these event generators is currently under way.

restrict ourselves to the 7 TeV LHC, and begin by studying a few fully-inclusive ones (see Figs. 1-4). We then consider a “boosted” case, *i.e.* apply a hard cut on the transverse momentum of the Higgs (see Figs. 5 and 6). Finally, in Figs. 7 and 8 we present our aMC@NLO predictions for correlations constructed with final-state  $B$  hadrons, which may or may not arise from the decays of the Higgs and/or of the tops (see a discussion on this point later).

We first note a very interesting feature of Fig. 1: the  $p_T$  distributions corresponding to the three different scenarios, while significantly different at small transverse momenta, become quite close to each other at higher values. This is expected from the known pattern of the Higgs radiation off top quarks at high  $p_T$  in both the scalar and the pseudoscalar cases [41, 42, 10]. This difference is not affected by NLO corrections, and could therefore be exploited to identify the parity of the coupling at low  $p_T$ . On the other hand, the independence of the parity and masses of the  $p_T$  distributions at high values implies that the boosted analyses can equally well be used for pseudoscalar states.

In general, we find that differences between LO and aMC@LO<sup>3</sup>, and between NLO and aMC@NLO, are quite small for observables involving single-inclusive distributions, see Figs. 1-3. The same remark applies to the comparison between LO and NLO, and between aMC@LO and aMC@NLO. However, if the cut  $p_T^{H/A} > 200$  GeV is imposed (boosted Higgs analysis), differences between LO and NLO (with or without showers) are more significant, and cannot be approximated by a constant  $K$ -factor.

As is obvious, the impact of the shower is clearly visible in the three-particle  $p_T(t\bar{t}H/t\bar{t}A)$  distribution of Fig. 4. This observable is infrared-sensitive at the pure-NLO level for  $p_T \rightarrow 0$ , where it diverges logarithmically. On the other hand, the predictions obtained after interfacing with shower do display the usual Sudakov suppression in the small- $p_T$  region. At large transverse momenta the aMC@NLO and NLO predictions coincide in shape and absolute normalisation, as prescribed by the MC@NLO formalism.

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<sup>3</sup>We call aMC@LO the analogue of aMC@NLO, in which the short-distance cross sections are computed at the LO rather than at the NLO. Its results are therefore equivalent to those one would obtain by using, *e.g.*, MADGRAPH/MADEVENT [43] interfaced to showers.

Scenario	Cross section (fb)					
	7 TeV			14 TeV		
	LO	NLO	$K$ -factor	LO	NLO	$K$ -factor
I	104.5	103.4	0.99	642	708	1.10
II	27.6	31.9	1.16	244	289	1.18
III	69.6	77.3	1.11	516	599	1.16

Table 1: Total cross sections for  $t\bar{t}H$  and  $t\bar{t}A$  production at the LHC ( $\sqrt{s} = 7, 14$  TeV), to LO and NLO accuracy. The integration uncertainty is always well below 1%. Scale choices and parameters are given in the text.

In our Monte Carlo simulations, we have included the  $t \rightarrow e^+ \nu b$ ,  $\bar{t} \rightarrow e^- \bar{\nu} \bar{b}$ , and  $H \rightarrow b\bar{b}$  decays at LO with their branching ratios set to one<sup>4</sup>. After showering, the  $b$  quarks emerging from the decays of the primary particles will result into  $b$ -flavoured hadrons. As prescribed by the MC@NLO formalism, the showering and hadronisation steps are performed by the event generator the NLO computation is matched to, *i.e.* HERWIG in this Letter. The parameters that control hadron formation through cluster decays are set to their default values in HERWIG [36]. Additional  $b$ -flavoured hadrons may be produced as a consequence of  $g \rightarrow b\bar{b}$  branchings in the shower phase. For example, for scalar Higgs production at 7 TeV, about 2.7% and 0.5% of events have six and eight lowest-lying  $B$  hadrons respectively. In our analysis, we have searched the final state for all lowest-lying  $B$  hadrons, and defined two pairs out of them. *a)* The pair with the largest and next-to-largest transverse momenta; *b)* the pair with the largest and next-to-largest transverse momenta among those  $B$  hadrons whose parent parton was one of the  $b$  quarks emerging from the decay of the Higgs (there are about 0.2% of events with four or six  $B$  hadrons connected with the Higgs). The definition of *b)* relies on MC truth (and in all cases we assume

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<sup>4</sup>We have neglected production angular correlations [44], as these are expected to have a minor impact for the kind of processes and observables we consider here. As usual when matching fixed order calculations to parton showers, colour information is transferred in the large- $N_C$  limit. The  $b$ -quark mass in the top and Higgs decay products has been set to the HERWIG default, 4.95 GeV.

100% tagging efficiency), but this is sufficient to study the basic features of final-state  $B$  hadrons.

In Figs. 7 and 8 we plot the pair invariant mass ( $m_{BB}$ ) and the  $\eta-\varphi$  distance ( $\Delta R_{BB}$ ) correlations between the  $B$ -hadron pairs defined as explained above. The effects of the NLO corrections to  $t\bar{t}H/t\bar{t}A$  are, in general, moderate. A cut of 200 GeV on the  $p_T$  of the Higgs is seen to help discriminate the  $B$  hadrons arising from the Higgs from those coming either from top decays, or from the shower. The shapes of the distributions are similar between scenarios I and II while, due to the lower Higgs mass, the  $m_{BB}$  and  $\Delta R_{BB}$  histograms peak at lower values in the case of a pseudoscalar  $A$  with  $m_A = 40$  GeV.

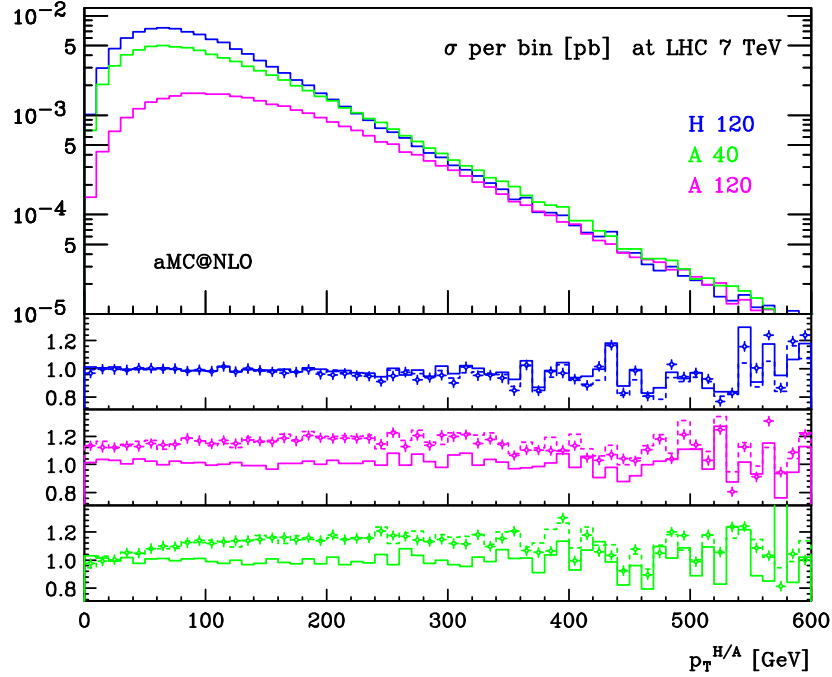


Figure 1: Higgs transverse momentum distributions in  $t\bar{t}H/t\bar{t}A$  events at the LHC ( $\sqrt{s}=7$  TeV), with aMC@NLO in the three scenarios described in the text: Scalar (blue) and pseudoscalar (magenta) Higgs with  $m_{H/A} = 120$  GeV and pseudoscalar (green) with  $m_A = 40$  GeV. In the lower panels, the ratios of aMC@NLO over LO (dashed), NLO (solid), and aMC@LO (crosses) are shown for each scenario.

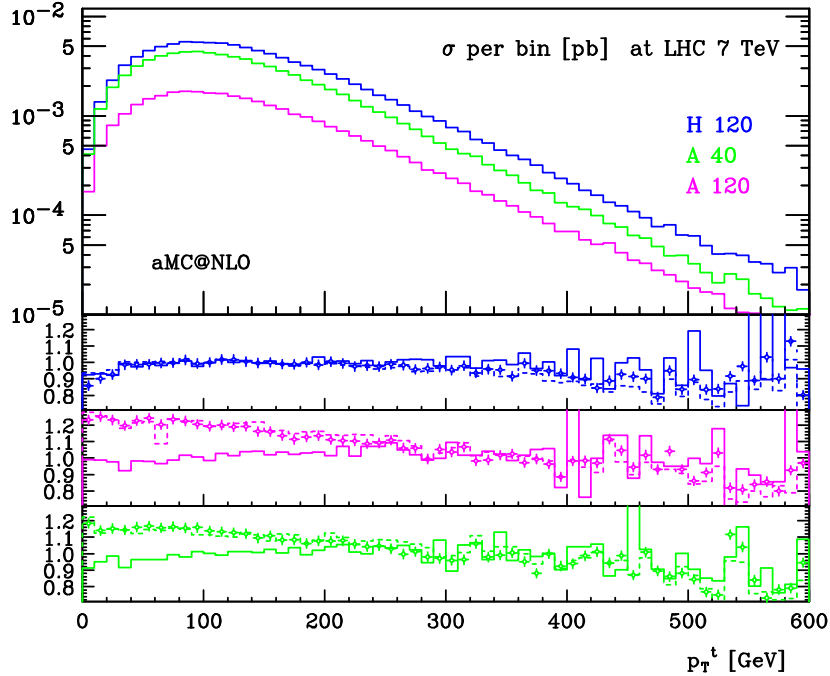


Figure 2: Same as in Fig. 1, for the  $p_T$  of the top quark.

### 3. Conclusions

Accurate and flexible predictions for Higgs physics will play an important role in understanding the nature of the EWSB sector in the standard model and beyond. In this Letter we have presented the results at NLO in QCD for (scalar and pseudoscalar) Higgs production in association with a top-antitop quark pair, both with and without the matching to parton showers. Our approach is fully general and completely automated. A simple study performed on key observables involving the Higgs, the top quarks, and their decay products shows that while changes in the overall rates can be up to almost +20% (for the pseudoscalar states) with respect to LO predictions, in general the shapes of distributions are mildly affected for a light SM Higgs. Significant changes, however, can be observed in the case of a light or very light pseudoscalar state.

The kernels of MC subtraction terms defined in the MC@NLO formalism, although process-independent, do depend on the specific event generator one adopts for the shower phase. In other words, each event generator requires a set of MC subtraction terms, which are computed analytically. Results are now available for the cases of Fortran HERWIG, HERWIG++,



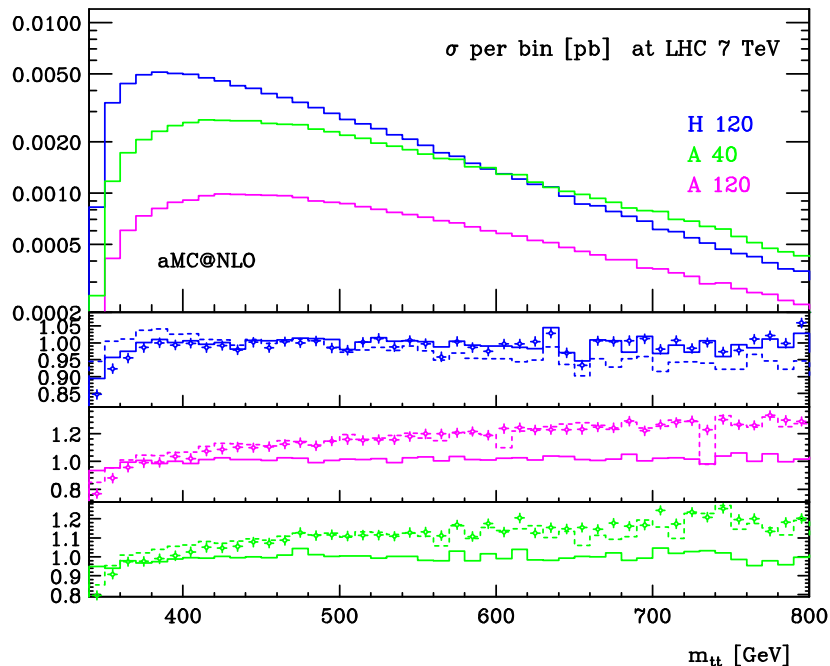


Figure 3: Same as in Fig. 1, for the invariant mass of the top-antitop pair.

and PYTHIA6; those relevant to the former program have been used to obtain the predictions presented here, while those relevant to the latter two codes are presently being automated and tested against known benchmarks.

We conclude by pointing out that work is in progress to make the use of aMC@NLO for  $t\bar{t}H/t\bar{t}A$  production and for other processes publicly available at <http://amcatnlo.cern.ch>.

#### 4. Acknowledgments

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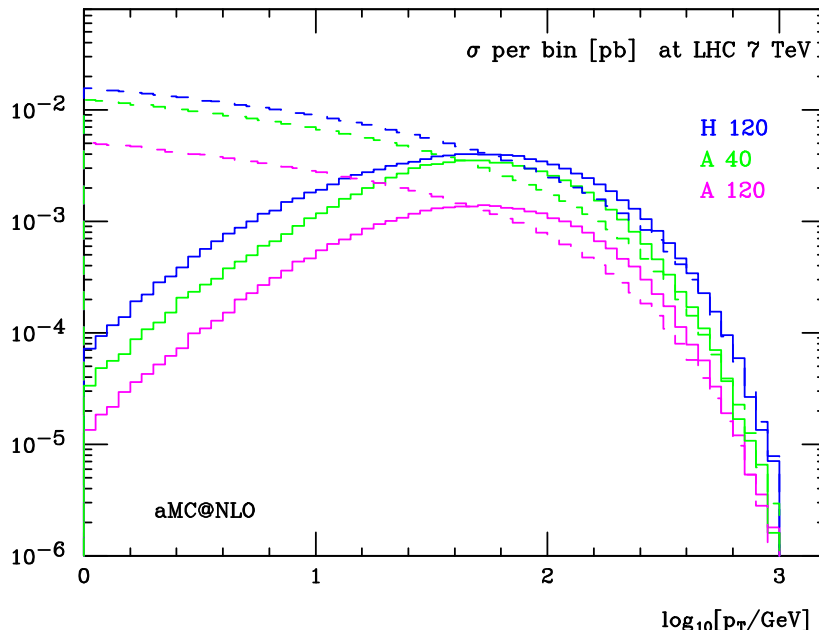


Figure 4: Transverse momentum of the  $t\bar{t}H$  or  $t\bar{t}A$  system. The same colour patterns as in Fig. 1 have been used. Solid histograms are aMC@NLO, dashed ones are NLO.

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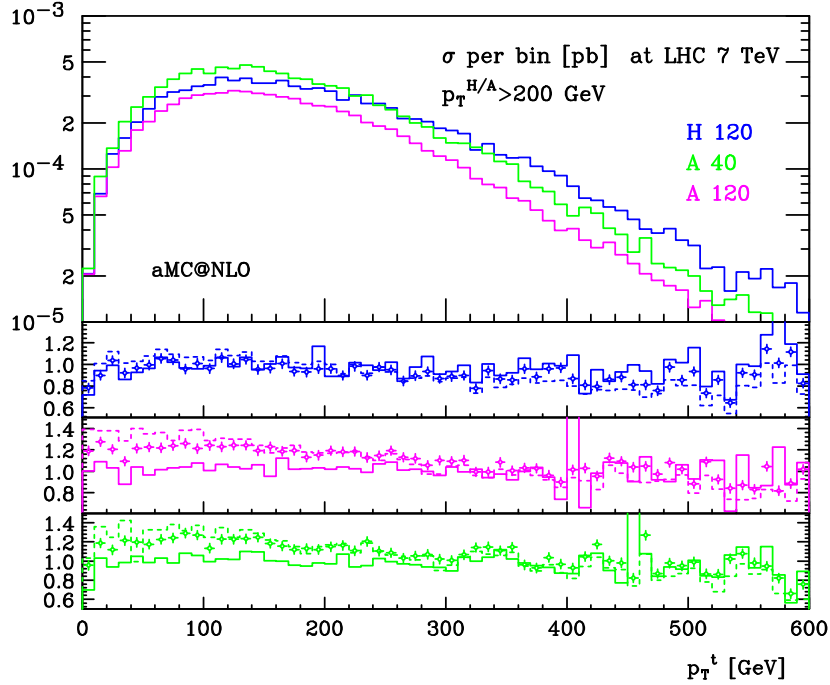


Figure 5: Same as in Fig. 1, for  $p_T$  of top quark when  $p_T^{H/A} > 200$  GeV.

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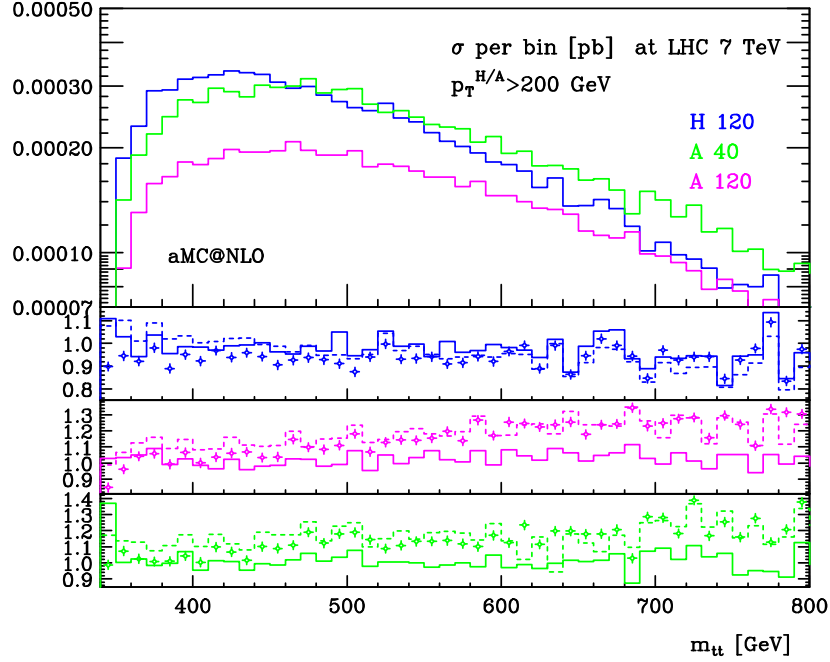


Figure 6: Same as Fig. 5, for the invariant mass of the top-antitop pair.

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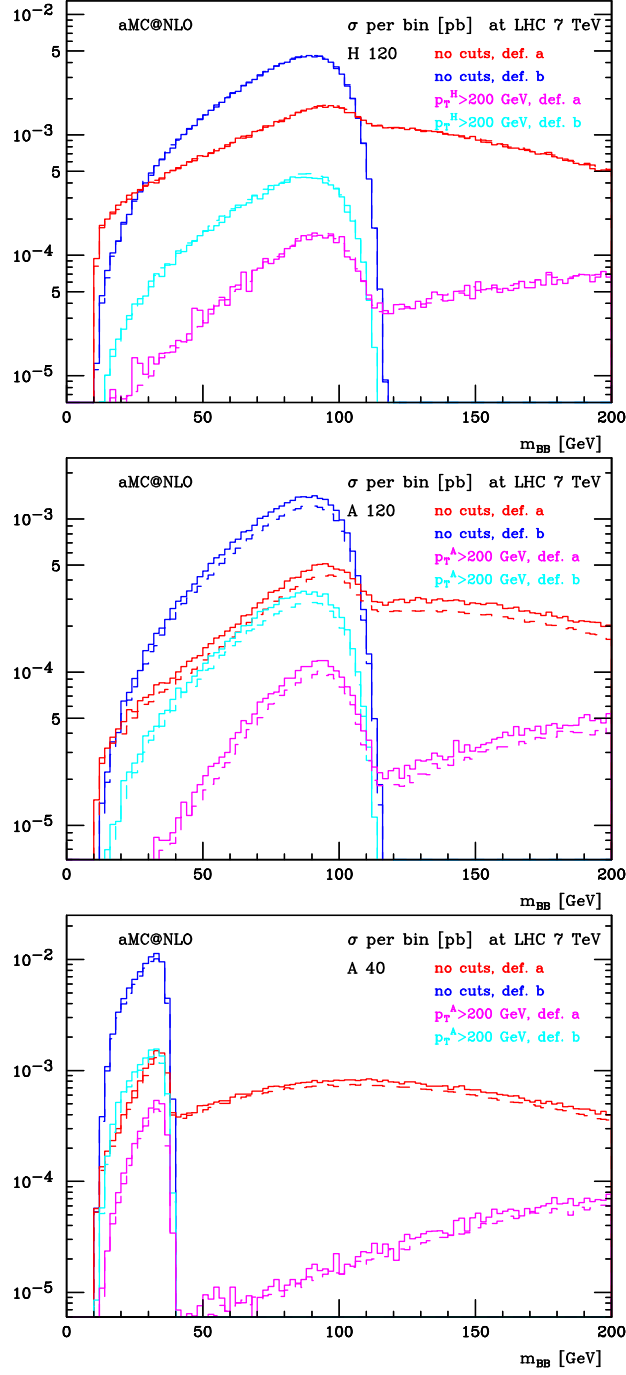


Figure 7: Invariant mass distributions of the  $B$ -hadron pairs defined as  $a$ ) (red) and  $b$ ) (blue) in the text. The results obtained by imposing  $p_T^{H/A} > 200$  GeV (magenta and cyan, respectively) are also displayed. Solid histograms are aMC@NLO, dashed ones are aMC@LO.

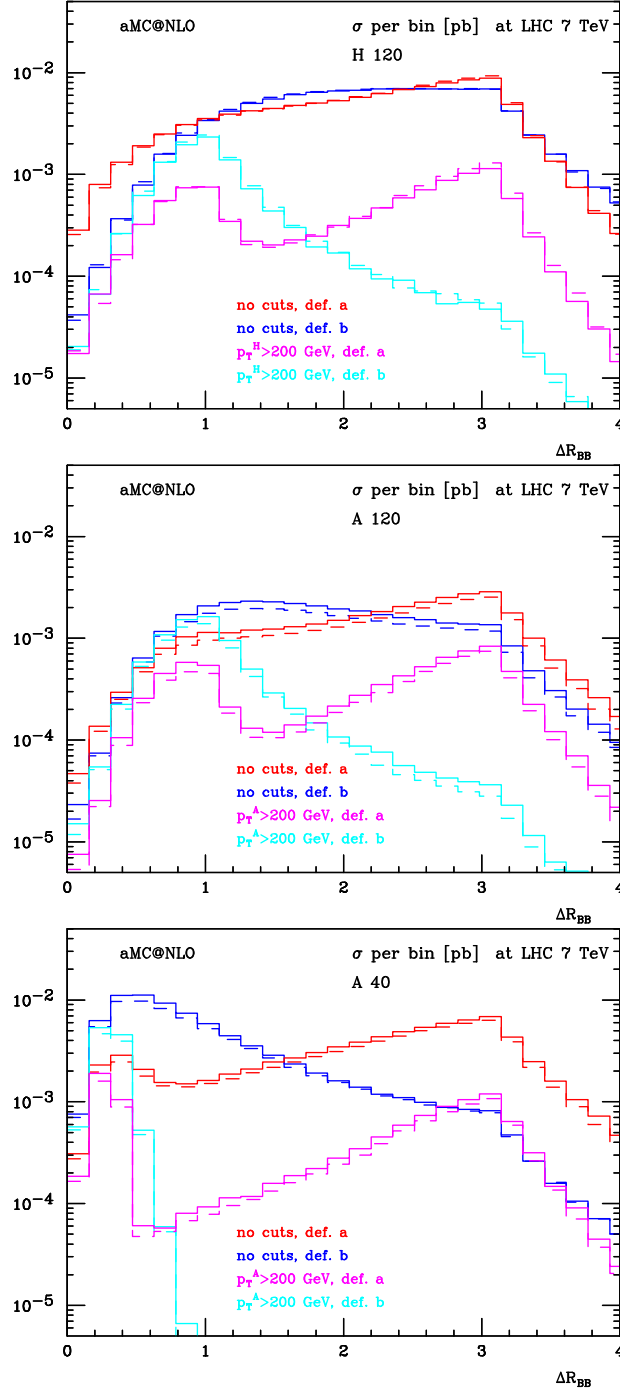


Figure 8: Same as in Fig. 7, for the  $\Delta R_{BB}$  correlation.